NATIONAL BUREAU OF STANDARDS REPORT

1817

FINAL REPORT

ON

INVESTIGATION ON AGGREGATES AND CONCRETES USED IN RIGID PAVEMENTS SUBJECTED TO HIGH AND FLUCTUATING TEMPERATURES

by

W. L. Pendergast, R. A. Heindl, C. R. Enoch, R. A. Clevenger

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INVESTIGATION ON AGGREGATES AND CONCRETES USED IN RIGID PAVEMENTS SUBJECTED TO HIGH AND FLUCTUATING TEMPERATURES

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W. L. Pendergast, R. A. Heindl, C. R. Enoch, R. A. Clevenger
Refractories Section
Mineral Products Division

Sponsored by
U. S. Naval Civil Engineering Research and Evaluation Laboratory, Construction Battalion Center, Port Hueneme, California.

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FINAL REPORT

June 30, 1952

INVESTIGATION ON AGGREGATES AND CONCRETES USED IN RIGID PAVEMENTS SUBJECTED TO HIGH AND FLUCTUATING TEMPERATURES

Technical Requirements

General: The objective of the project is the design of heat-resisting concretes suitable for use in rigid pavements for general ground circulation of jet-type aircraft and especially for warm-up, power check, and take-off operations of the aircraft.

Detail Requirements: The concretes must be of sufficient strength to withstand loads to which they will be subjected. Therefore, a minimum compressive strength of 2600 psi is specified. The concretes must have a maximum resistance to destruction when exposed to rapidly increasing and fluctuating temperatures.

I. INTRODUCTION

That phase of the project "Investigation of Aggregates and Concretes Used in Rigid Pavements Subjected to High and Fluctuating Temperatures," to be studied at the National Bureau of Standards was discussed at a meeting during June, 1951. Dr. Herbert Insley, R. L. Blaine, R. A. Heindl, and your Mr. Perry Petersen were present. It was concluded that such properties as refractoriness, thermal expansion, resistance to abrasion, heat transfer, compressive strength, and modulus of elasticity should be determined. The types of cements and aggregates that were to be used in designing the concretes were also selected at this time.

II. MATERIALS

The cements were (1) portland, a product of the North American Cement Company, (2) Green Bag portland pozzolan, a product of the Pittsburgh Coke and Chemical Company in which the pozzolanic agent is a blast furnace slag, and (3) Lumnite, a high-alumina hydraulic cement, manufactured by the Universal Atlas Cement Company.

Twelve aggregates were selected on the basis of both availability and possible suitability. Five of this group were classified as light weight aggregates and the other seven as more refractory and of a non-light weight classification. The light-weight group included two expanded shales "Lelite" and "Haydite," a clay-coated expanded shale "Rocklite," an expanded slag "Waylite," and a pumice from California. The non-light weight group included an olivine (an iron-magnesium silicate from North Carolina), "Bluestone" (a limestone from Western Maryland), a medium dense common building brick, a portland cement clinker, gravel and sand known as "White Marsh," and a Kentucky flint clay. The flint clay, which contained considerable iron pyrites and therefore unsuitable for firebrick manufacture, was submitted in two lots. One lot was received in the green state, that is as mined, the second had been calcined at about 1250°C.

A detailed description of the light weight aggregates was given in a publication by the Housing and Home Finance Agency.1/

III. METHODS OF PREPARATION AND TESTING

A. Refractoriness. The pyrometric cone equivalent[2/] or refractoriness of the cements, aggregates, and concretes was determined in a gas-heated furnace except the calcined flint clay. A carbon resistence furnace was used for this determination.

1. Cements. The portland and portland pozzolan cements were tested* in accordance with Federal Specifications SS-C-192, Type I, and SS-C-208a, respectively. There are no Federal Specifications for hydraulic cements of the high-alumina type. Lumnite cement, therefore, was tested in accordance with SS-C-192, Type III.

2. Aggregates. The crushing strength of the aggregates was determined by employing the methods described in a Bureau of Reclamation publication.[3/] All other tests, with slight modifications necessitated by the characteristics of the material, were conducted in accordance with the methods described in the "1950 ASTM Standards on Mineral Aggregates, Concrete, and Nonbituminous Highway Materials."

3. Concretes. The data on aggregate sizing and the cement-aggregate ratio given in the publication,[1/] issued by the Housing and Home Finance Agency, was used to advantage

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* Made by the Mineral Products Division, Concreting Materials Section, National Bureau of Standards.

in designing the concretes. The mixes were adjusted to compensate for differences existing between sizes of the aggregates used in this study and those listed in that publication. The concretes were proportioned by volume and mixed in a three cubic foot tilt-drum mixer. The water and aggregate were mixed for one minute, the cement and an air-entraining agent, vinsol resin, were then added in that order, and the complete batch mixed for an additional three minutes. The concrete was then placed in specimen molds and the surface finished immediately with a wood float. Each batch contained sufficient concrete for the following specimens: four 6 x 12 inch cylinders, two 3 x 4 x 16 inch prisms, one 24 x 24 x 2 1/2 inch slab, and two 8 x 8 x 1 1/4 inch plates. The 24-inch slab, after partial set, received an additional delayed finishing with a steel trowel. All specimens were covered with wet burlap until the end of a 24-hour period. They were then removed from the molds, cured for six days in a fog-room and stored at laboratory temperature and humidity for 21 days. Because it was planned to test each concrete after curing, and also after five different heat treatments, limitations of laboratory facilities made it necessary to fabricate separate lots of specimens of each concrete on subsequent days.

Specimens of each concrete were tested after a curing period of 28 days and also after each of the following heat treatments: 250, 500, 750, and 1000°C respectively. The temperature of the kiln in which the specimens were heat-treated was increased approximately 50°C per hour to the maximum scheduled temperature. After temperature equilibrium was reached, throughout the specimens the kiln was held at the maximum temperature for five hours. The specimens were cooled in the kiln to room temperature.

Fifteen concretes were designed and tested using portland, Green Bag, and Lumnite cement, respectively, with each of five aggregates, namely pumice, Haydite, Waylite, Rocklite, and Lelite.

The linear thermal expansion will be determined of concrete specimens to the maximum possible temperature depending on their refractoriness. For this purpose specimens have been prepared measuring 1 x 1 1/2 x 7 1/2 inches.

Measurements of the thermal conductivity of the concretes were made* using the hot-plate apparatus shown in Figure 1. It consists of an electrically heated hot-plate 8 inches square, set in a horizontal plane, and a cold plate of the same size cooled by n-pentane (C_5H_{12}) boiling at atmospheric pressure (i.e., at approximately 98°F).

* Thermal conductivity measurements were made by the Building Technology Division, Heating and Air Conditioning Section of the National Bureau of Standards.

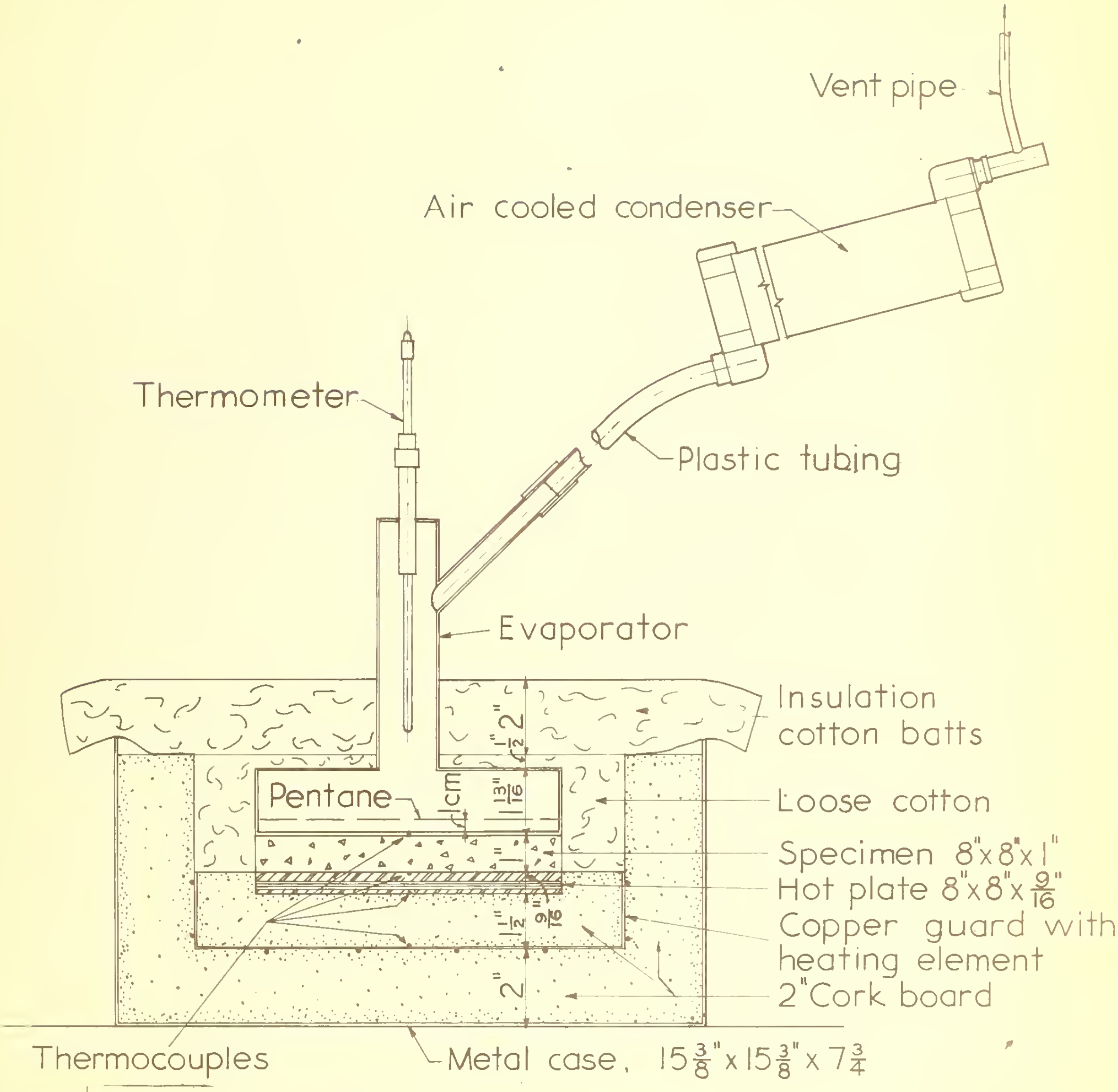

FIG. 1 – Hot plate thermal conductivity tester

The pentane vapor was condensed in an air-cooled condenser arranged so that the condensate returned to the cold plate.

The test specimen, 8 inches square and approximately one inch thick, was placed between the hot and cold plates. The contacting surfaces of the plates and of the specimens were ground flat to assure good thermal contact between them. Copper-constantan thermocouples were set in the surfaces of the hot and cold plates to measure their temperatures. Heat flow downward and outward from the edges of the hot-plate was made substantially zero by means of an electrically-heated copper guard pan placed under and around the hot-plate with insulation between them, by adjusting the guard to the same temperature as the underside of the hot-plate, as indicated by the thermocouples attached thereon.

The tests were conducted with the hot-plate at about 140°F and the cold plate at about 98°F. When steady temperatures were attained with the guard properly adjusted, the electrical power input to the hot-plate and the temperatures of the hot and cold plate surfaces in contact with the specimen were measured. The thermal conductivity (k) of the specimen, expressed in Btu per hour per square foot per degree F per inch temperature gradient, was calculated from these data combined with measurements of the area and thickness of the specimen.

The test apparatus was checked by a series of comparison tests made in the Bureau's guarded hot-plate conductivity apparatus, conforming to ASTM C-177, on a specimen having a conductivity of 0.8. Agreement between the tests in the two sets of apparatus was within 1.1 percent.

The cast specimens were prepared with flat and parallel faces by grinding, and were dried in a ventilated oven at 220°F for 72 hours prior to test. The duration of a test was from 7 to 24 hours, depending upon the time necessary to attain steady temperature conditions. The specimen was weighed immediately before and after test.

The resistance of the concretes to abrasion was determined using the apparatus designed by Schuman and Tucker.[4/]

The compressive strength of the concretes was determined in accordance with ASTM Method Designation C39-44.[5/]

Young's modulus of elasticity was determined in accordance with the method described by Gerald Pickett.[6/]

Other properties and pertinent data relating to the concretes were determined as follows. The proportion, by weight, of cement to coarse to fine aggregate was arrived at using available information on concretes designed with similar aggregates. The same procedure was followed in determining the amount of vinsol resin to be added.

The cement content, air content, and weight of fresh concrete was determined according to ASTM Designation C138-44.[5/]

The water content was calculated by the following formula:

$$\text{Water content} = \frac{\text{Mixing water in gallons}}{\text{Volume of concrete yielded in cubic yards}}$$

The slump of the fresh concrete was determined according to ASTM Designation C143-39.[5/]

The weight per cubic foot of concrete after curing or after heat-treatment was calculated by the formula:

$$\text{Weight per cubic foot} = \frac{\text{Weight in pounds}}{\text{Volume in cubic feet}}$$

The strength-weight ratio was calculated using the formula:

$$\text{Strength-weight ratio} = \frac{\text{Compressive strength } (lb/in^2)}{\text{Weight } lb/ft^3}$$

The linear shrinkage, based on the inner dimension of the mold, was calculated using the formula:

$$\text{Linear shrinkage} = \frac{lo - lf}{lo} \times 100$$

where:

lo = original length

lf = final length

IV. RESULTS AND DISCUSSION

A. Refractoriness or Pyrometric Cone Equivalent.

Table 1 gives the pyrometric cone equivalent (PCE) of the cements, aggregates, and concretes. Although portland cement is appreciably more refractory than the high-alumina cement, PCE of 18 versus 14, nevertheless, it is not considered satisfactory for use in heat-resistent concrete. The reason for this fact is that portland

cement, after dehydration and heating may form beta-dicalcium silicate which in turn will convert to gamma-dicalcium silicate. Such an inversion is attended by a marked volume change causing the product to "dust," which in turn results in a marked loss in bonding strength. Inasmuch as silica is a minor constituent of Lumnite there is an insignificant amount (if any) of dicalcium silicate formed and consequently in this cement no "dusting" occurs. The tests indicate a wide range of refractoriness in aggregates, namely, Cone 2 for pumice and Rocklite to Cone 31 for flint clay. The results of the PCE determination of the concretes indicate that the substitution of Lumnite cement for either portland or portland pozzolan increased the refractoriness of all concretes except that containing Waylite. The concretes designed using pumice as an aggregate showed definite indication of fusion at 1000°C. However, when Rocklite, the other aggregate with a low PCE was used, there was no indication of fusion at 1000°C.

Table 1

Pyrometric Cone Equivalents (PCE)

of

Cements, Aggregates, and Concretes

Cement	Aggregate	Cement Aggregate ratio by weight	PCE	Equivalent approximate temperature (°C)
Portland	---	---	18	1490
Portland pozzolan	---	---	14	1400
Lumnite	---	---	14-15	1420
---	Pumice	---	2	1165
---	Rocklite	---	2	1165
---	Haydite	---	6	1230
---	Lelite	---	10	1305
---	Waylite	---	13	1350
---	Common building brick	---	15-16	1450
---	Flint clay calcined	---	31	1680
Portland and	Pumice	1 : 1.5	5	1205
do do	Rocklite	1 : 3.9	4	1190
do do	Haydite	1 : 3.6	4	1190
do do	Waylite	1 : 2.4	14-15	1420
Portland pozzolan and	Pumice	1 : 1.5	4	1190
do do	Rocklite	1 : 3.9	4	1190
do do	Haydite	1 : 3.6	3 - 4	1180
do do	Waylite	1 : 2.4	14	1400
Lumnite and	Pumice	1 : 1.5	7 - 8	1255
do do	Rocklite	1 : 3.9	5 - 6	1220
do do	Haydite	1 : 3.6	9	1285
do do	Waylite	1 : 2.4	12	1335

1. Cements. The results of the physical tests and chemical analyses are given in tables 2 and 3.

Table 2. Results of Physical Tests of Cements

Cement	Time of set Initial	Time of set Final	Surface Blaine a/ apparatus	Compressive Strength 3-day	Compressive Strength 7-day	Compressive Strength 28-day	Air Content	Autoclave Expansion
	Hr. Min.	Hr. Min.	cm^2g	lb/in^2	lb/in^2	$lb/in.^2$	%	%
Portland	4 : 40	7 : 00	3340	1040	2040	3820	8.0	0.10
Portland pozzolan	4 : 45	7 : 05	3770	1170	1780	3370	13.2	0.02
High - alumina	11 : 30	13 : 15	--	4280	4360	5200	5.4	0.02

Table 3. Chemical Analysis of Cements

Cement	Ignition Loss	Insol. Residue	SO_3	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Total alkali as Na_2O	K_2O	FeO
	%	%	%	%	%	%	%	%	%	%	%
Portland	1.9	0.2	1.7	21.6	5.7	2.6	62.4	3.1	0.30	0.84	
Portland pozzolan	0.0	0.3	1.7	24.7	7.7	2.2	59.4	1.8	0.05	0.44	2.0
High-alumina	-0.1 b/	1.7	0.3	8.6	42.7	4.3	36.8	0.8	--	--	6.2

a/ Tentative method of Test for Fineness of Portland Cement by Air Permeability Apparatus A.S.T.M. Designation: C204-46T, 1946

b/ Gain

The portland cement complied with the technical requirements of Federal Specification SS-C-191. The portland pozzolan, however, failed to comply with the required compressive strength (1800 psi) after seven-day aging.

The outstanding difference in the chemical compositions of the three cements is that Lumnite contains a much higher percentage of alumina and considerably less calcium oxide and silica.

The setting of portland cement is due to the formation of hydrated calcium silicate. Because Lumnite contains only small amounts, if any, of the silicates its setting is the result of the formation of hydrated calcium aluminates and hydrated alumina. Since the aluminates hydrate more rapidly than the silicates, a high-alumina cement, such as Lumnite, develops a high early strength as indicated in table 2.

2. Aggregates. Table 4 gives the screen analysis and some properties of the aggregates. This information aided in the designing of the concretes. Two general sizings of aggregates were used in each concrete. One of these sizings designated as "coarse" consisted primarily of material retained on a No. 4 and passing a one inch screen. The other designated as "fines" consisted of material passing a 3/8 inch screen.

ific ity . Dry (c)	Water Absorption Percent by weight	Crushing strength lbs/in^2 (d)		
		Compaction, inches		
		1	2	3
74 64	0.24 1.06	(f)	--	--
66 08	11.28 8.61	1,535	13,863	41,062 (f)
65 09	8.42 5.50	561	3,244	39,824 (f)
68 38	17.10 2.61	264	943	8,450
26 43	39.00 44.80	396	1,563	6,465
32 65 81 97	10.54 10.22 17.80 17.10	2,780 (e)	28,299 (e)	41,026 (e)
26 27 37	8.93 9.60 6.10	-- -- --	-- -- --	-- -- --
65 65	0.90 0.80	3,930	41,030 (f)	--
52 50	4.76 5.03	778	13,074	40,682 (f)
97	3.20	--	--	--

Table 4. Properties of Aggregates

Materials: Identification	Materials: Size	Sieve Analysis — Amount passing U. S. Standard Sieve, percent by weight: 1"	3/4"	1/2"	3/8"	Nos. 4	8	16	30	50	100	200	Fineness Modulus (a)	Unit Weight lbs/ft³: Loose	Jigged (b)	Bulk Specific Gravity S.S. Dry (c)	Water Absorption Percent by weight	Crushing strength lbs/in² (d) Compaction, inches: 1	2	3
Bluestone	Coarse	100.0	99.1	71.6	22.7	3.1	2.0	--	--	—	—	—	6.73	83.6	98.0	2.74	0.24			
	Fine	--	--	--	100.0	99.3	79.6	50.7	26.7	11.5	3.7	11.3	3.28	99.8	113.0	2.64	1.06	(f)	—	—
Haydite	Coarse	—	100.0	95.3	71.1	11.1	1.8	--	--	--	--	—	6.16	53.8	62.1	1.66	11.28			
	Fine	--	--	--	100.0	99.8	95.3	70.7	43.5	27.4	18.3	12.6	2.45	68.1	97.5	2.08	8.61	1,535	13,863	41,062 (f)
Lelite	Coarse	99.9	97.9	75.5	40.3	8.5	6.8	—	--	--	--	--	6.46	42.4	47.9	1.65	8.42			
	Fine	--	--	--	--	100.0	97.3	68.0	42.7	26.6	16.8	10.8	2.48	63.9	73.1	2.09	5.50	561	3,244	39,824 (f)
Waylite	Coarse	--	—	100.0	94.2	16.8	8.8	--	--	--	--	--	5.80	33.2	39.4	1.68	17.10			
	Fine	--	--	--	100.0	99.9	97.3	84.6	54.9	32.0	15.2	5.9	2.16	60.4	72.2	2.38	2.61	264	943	8,450
Pumice	Coarse	100.0	98.7	82.5	51.0	16.8	15.4	--	--	--	—	--	6.18	29.2	32.1	1.26	39.00			
	Fine	--	--	--	100.0	76.3	46.2	32.8	21.8	14.3	8.1	13.5	4.01	38.6	43.9	1.43	44.80	396	1,563	6,465
Rocklite	Coarse	100.0	78.9	--	--	--	--	--	--	--	--	—	7.21	47.7	52.0	1.32	10.54			
	Thru 9/16	—	100.0	98.9	59.9	0.7	--	--	--	--	—	—	6.39	51.3	57.0	1.65	10.22			
	Thru 5/16	—	--	--	100.0	44.5	1.3	—	--	--	--	--	5.54	55.3	61.9	1.81	17.80	2,780 (e)	28,299 (e)	41,026 (e)
	Fine	--	—	--	100.0	99.8	78.7	40.0	20.6	9.5	3.9	—	3.48	66.3	73.3	1.97	17.10			
Building Brick	Coarse	100.0	99.1	66.8	15.2	4.4	3.9	—	--	--	--	--	6.77	61.4	71.9	2.26	8.93	—	--	--
	Medium	--	--	100.0	98.3	16.5	5.4	4.3	--	--	--	--	5.75	60.5	70.3	2.27	9.60	--	--	--
	Fine	--	--	--	100.0	99.9	70.9	50.5	36.0	23.5	11.0	7.5	3.08	80.1	91.9	2.37	6.10	--	--	--
Flint-clay Calcined	Coarse	100.0	99.6	85.3	70.4	44.2	24.9	--	--	--	—	—	5.60	87.7	101.7	2.65	0.90			
	Fine	--	—	--	100.0	75.1	38.0	20.2	10.6	5.2	1.8	0.9	4.49	89.4	101.3	2.65	0.80	3,930	41,030 (f)	--
Flint-clay Raw	Coarse	100.0	99.8	83.2	69.8	45.5	29.3	--	--	--	--	--	5.55	86.0	101.5	2.52	4.76			
	Fine	--	--	--	100.0	76.3	37.3	20.1	10.2	4.6	1.5	1.9	4.50	80.9	95.0	2.50	5.03	778	13,074	40,682 (f)
Olivine	Coarse	--	100.0	85.3	70.9	54.3	45.6	--	--	--	--	--	5.29	124.8	146.7	2.97	3.20	—	--	--
	Fine	--	—	--	100.0	99.9	99.3	82.0	65.5	35.2	10.3	4.0	2.08	114.4	130.5	3.09	1.00	--	--	--
White Marsh Gravel	Coarse	89.9	76.2	54.1	31.9	3.3	--	—	--	--	—	--	6.88	101.1	110.9	2.64	0.30	—	—	--
Sand	Fine	--	--	--	100.0	97.9	8.00	64.9	49.5	22.0	4.1	1.2	2.82	100.4	112.0	2.63	0.30	--	--	--

(a) Indicates distribution of sizes of aggregate as determined by ASTM method C125-43 "Standard Definitions of Terms Relating to Concrete and Concrete Aggregates", ASTM Standards on Mineral Aggregates, Concrete, and Nonbituminous Highway Materials, Sept. 1948, page 70.

(b) Indicates bulking or fitting together of various sizes of aggregates.

(c) "S.S." Saturated aggregate - Surface Dry.

(d) Grading - 50% through 3/8" retained on No. 4; 30% through No. 4 retained on No. 8; 20% through No. 8 retained on No. 16.

(e) Rocklite - 60% through No. 4 retained on No. 8; 40% through No. 8 retained on No. 16.

(f) Bluestone beyond capacity of apparatus at 1" compaction;
Flint clay (calcined) maximum compaction possible with apparatus 1 13/16"
Haydite " " " " " 2 21/64"
Lelite " " " " " 2 23/64"
Flint Clay (Raw) " " " " " 2 9/16"

The screen analyses were necessary to determine the distribution of the particle sizes. From these analyses the fineness moduli of both the "fines" and the coarse were calculated. The modulus of the "fines" should not exceed a value of approximately 3.2. The fineness modulus of the combined mixture of fine and coarse aggregate is calculated in accordance with the respective proportions of each used in the concrete mix. It is not considered desirable that this value exceed approximately 5.2. Two of the fineness moduli of the "fines" as given in table 4, were above the limit of 3.2 and the combined fineness moduli of the same two aggregates were slightly above 5.2. This data refers only to the five light-weight aggregates reported. Values outside these limits tend to develop a harsh concrete with a high percentage of voids, resulting in a loss of strength.

It must be recognized that the fineness modulus does not apply perfectly to light-weight aggregates since it was founded on data using normal aggregates. The bulk specific gravity factor adjusts the mix to the proper proportion, by weight, as compared to volume. The water absorption of the aggregate determines the amount of excess mixing water to add to the cement-water ratio. The crushing strength in compaction indicates the maximum strength obtainable with that aggregate. The strength of the resulting concrete, however, also depends on the shape and condition of the surface of the aggregate.

dulus city c/ L tongitudinal I c After heating	Linear Shrinkage d/ Before heating	After heating	Abrasion Loss
x 10^6	%	%	gms
—	—	—	—
—	—	—	—
—	—	—	—
—	0.000	0.766	—
—	0.050	4.990	—
—	—	—	—
—	—	0.650	—
—	—	—	—
—	0.067	0.916	—
—	0.130	2.210	—
—	0.116	—	—
—	—	—	—
—	—	—	—
—	0.083	—	—
—	0.170	—	—
—	—	—	—
1.373	0.083	0.216	—
1.360	0.110	0.180	44.3
0.560	0.000	0.450	625.5
0.527	0.217	-0.166	—
—	0.100	—	—
—	—	—	—
1.160	0.166	0.216	—
0.922	0.060	0.190	50.0
0.594	0.100	0.430	338.4
0.434	0.317	-0.183	—

ncrete mixes of the
will show any

Table 5. Properties of Heat-Resisting Concretes

Laboratory Identification a/	Proportions by weight Cement to coarse and to fine aggregate	Cement Content	Vinsol resin by weight of cement	Water Content	Air Content	Slump on fresh concrete	Weight of fresh concrete	Weight of Concrete after 7-day fog 21-day R.T.	Weight of Concrete after Heat treatment c/	Compressive Strength 6 x 12 in. cylinder	Strength weight ratio	Young's modulus of elasticity c/ Dynamic Longitudinal Before heating	Young's modulus of elasticity c/ Dynamic Longitudinal After heating	Linear Shrinkage d/ Before heating	Linear Shrinkage d/ After heating	Abrasion Loss
		Bags/yd^3 of concrete	%	Gal/yd^3 of concrete	%	inches	lbs/ft^3	lbs/ft^3		lbs/in^2		lb/in^2 x 10^6		%	%	gms
P-P-1	1:1:0.4	7.1	0.02	72	14.5	3.00	81	74	—	1470	19.9	0.852	—	—	—	—
P-P-2	1:1:0.5	6.8	do	72	16.2	2.25	80	—	—	1610	—	—	—	—	—	—
P-P-3	do	6.4	do	72	18.7	5.75	76	—	59	1150	19.5	—	—	—	—	—
P-P-4	do	6.6	do	74	13.9	0.00	79	73	57	455	8.0	—	—	0.000	0.766	—
P-P-5	do	6.6	do	72	15.7	5.50	79	70	—	85 e/	--	0.714	—	0.050	4.990	—
Z-P-1	do	6.4	do	71	17.1	5.25	77	70	—	1255	17.9	0.731	—	—	—	—
Z-P-2	do	7.1	do	78	9.6	2.25	85	—	62	1500	24.4	--	—	—	0.650	—
Z-P-3	do	5.7	do	65	25.5	7.50	68	—	61	665	10.9	—	—	--	—	—
Z-P-4	do	6.6	do	79	12.1	5.25	80	71	57	385	6.8	--	—	0.067	0.916	—
Z-P-5	do	6.6	do	71	15.8	4.75	78	68	—	95 e/	—	0.749	—	0.130	2.210	—
L-P-1	do	6.9	do	83	7.2	6.75	85	68	—	560	8.2	0.535	—	0.116	—	—
L-P-2	do	7.1	do	86	12.5	0.25	88	—	—	415	—	—	—	—	—	—
L-P-3	do	6.0	do	74	18.7	7.50	74	—	61	—	--	—	—	--	—	—
L-P-4	do	6.8	do	81	9.5	5.00	83	73	—	—	--	—	—	0.083	—	—
L-P-5	do	6.5	do	75	14.1	6.00	79	71	—	--	—	0.743	—	0.170	—	—
P-H-1	1:1.7:1.9	5.2	do	57	11.4	6.75	101	97	—	1750	18.1	1.930	—	—	—	—
P-H-2	do	5.3	do	54	11.2	3.63	101	99	91	2200	24.2	2.128	1.373	0.083	0.216	—
P-H-3	do	5.7	do	58	5.2	2.25	109	104	94	1670	17.3	2.455	1.360	0.110	0.180	44.3
P-H-4	do	5.1	do	56	11.5	2.75	101	102	92	580	6.3	2.313	0.560	0.000	0.450	625.5
P-H-5	do	5.6	do	57	6.6	2.75	107	102	90	290	3.2	2.340	0.527	0.217	-0.166	--
P-H-1	do	5.3	do	54	11.5	5.25	102	99	—	2070	20.1	2.032	—	0.100	—	—
Z-H-1	do	—	do	—	--	--	—	—	—	—	—	—	—	—	—	—
Z-H-2	do	5.1	do	54	13.3	6.63	99	97	89	2000	22.5	1.788	1.160	0.166	0.216	—
Z-H-3	do	5.3	do	54	12.4	5.75	100	98	90	1445	16.0	2.089	0.922	0.060	0.190	50.0
Z-H-4	do	5.2	do	55	13.2	4.50	99	99	90	595	6.5	2.054	0.594	0.100	0.430	338.4
Z-H-5	do	5.4	do	55	10.1	6.00	103	98	88	240	2.7	2.080	0.434	0.317	-0.183	—
L-H-1	do	5.5	do	60	6.8	2.75	106	100	—	2145	21.5	2.011	—	0.200	—	—
L-H-2	do	5.5	do	59	6.4	3.50	106	101	94	890	9.5	1.993	0.899	0.100	0.316	—
L-H-3	do	5.5	do	58	8.4	3.25	105	101	92	705	7.6	2.020	0.596	0.130	0.110	342.5
L-H-4	do	5.2	do	58	11.5	4.50	100	99	90	540	6.0	1.928	0.473	0.210	0.230	2266.0
L-H-5	do	5.6	do	60	5.2	5.50	107	101	89	310	3.5	2.090	0.509	0.316	-0.183	—
P-W-1	1:0.9:1.5	7.0	0.01	69	11.4	0.00	103	98	—	1535	15.6	1.880	—	0.260	—	140.8
P-W-2	do	6.7	do	67	14.6	1.75	99	95	89	1295	14.6	1.740	1.030	0.100	0.280	169.2
P-W-3	do	6.8	do	67	13.4	1.50	101	—	85	1150	13.5	—	0.719	—	0.350	—
P-W-4	do	6.7	do	66	15.0	2.50	99	94	81	—	—	1.684	—	0.300	-0.080	—
P-W-5	do	6.4	do	69	15.6	5.50	97	92	78	68	—	1.542	—	0.130	-0.650	—
Z-W-1	do	6.7	do	66	14.8	2.75	95	91	—	1420	15.6	1.410	—	0.000	—	67.2
Z-W-2	do	6.6	do	67	15.3	1.50	98	92	89	1135	12.7	1.577	0.856	0.000	0.130	173.8
Z-W-3	do	6.6	do	62	18.0	2.20	96	—	82	965	11.8	—	0.629	—	0.330	—
Z-W-4	do	6.6	do	63	17.3	2.50	96	90	81	415	5.1	1.513	0.451	0.060	0.400	—
Z-W-5	do	6.4	do	70	15.7	3.00	97	89	78	122	1.5	1.399	—	0.120	-0.420	—
L-W-1	do	6.8	do	68	13.0	0.13	101	96	—	1660	17.5	1.723	—	0.130	—	203.6
L-W-2	do	6.4	do	68	16.4	2.50	96	93	86	565	6.6	1.565	0.618	0.300	0.360	299.2
L-W-3	do	7.0	do	70	10.0	0.00	104	—	85	520	6.1	—	0.336	—	0.900	—
L-W-4	do	6.7	do	70	13.3	2.00	100	93	83	543	6.5	1.607	0.445	0.160	0.200	—
L-W-5	do	6.6	do	70	13.6	1.25	99	93	82	303	3.7	1.663	—	0.200	-0.650	—
P-R-1 f/	1.0:0.4:0.8:0.8:1.9	4.6	0.02	50	17.3	6.75	94	93	—	2110	22.7	1.865	—	0.180	—	100.3
P-R-2	do	4.7	do	51	15.0	2.00	96	92	84	2205	26.2	1.946	1.452	0.150	0.110	29.8
P-R-3	do	4.2	do	51	16.3	7.00	94	91	—	—	—	1.777	—	0.100	—	—
P-R-4	do	4.8	do	55	12.4	2.00	98	91	82	576	7.0	1.936	0.997	0.000	0.100	—
P-R-5	do	4.9	do	54	11.4	1.00	100	96	86	445	4.5	2.109	0.707	0.100	0.470	448.8
Z-R-1	do	4.5	do	50	18.7	5.25	92	91	—	2770	30.4	1.855	—	0.130	—	51.4
Z-R-2	do	4.9	do	53	12.5	1.25	99	93	86	2755	32.0	1.943	1.447	0.040	0.080	34.1
Z-R-3	do	4.2	do	52	18.5	7.00	91	88	—	—	—	1.719	—	0.000	—	—
Z-R-4	do	4.8	do	54	12.2	1.25	99	92	84	960	11.4	2.029	0.929	0.090	0.330	—
Z-R-5	do	4.9	do	54	11.3	0.00	101	92	84	515	6.1	1.877	0.755	0.300	0.540	583.0
L-R-1	do	5.0	do	55	9.8	0.50	102	97	—	2350	24.3	1.794	—	0.080	—	110.6
L-R-2	do	4.5	do	53	16.5	6.75	93	90	82	445	5.4	1.615	0.692	0.170	0.180	785.0
L-R-3	do	4.5	do	55	12.8	1.25	98	91	—	—	—	1.723	—	0.110	—	—
L-R-4	do	4.7	do	55	14.1	4.00	96	92	84	470	5.6	1.828	0.551	0.190	0.250	—
L-R-5	do	4.9	do	57	9.4	0.50	102	95	86	515	6.0	1.839	0.619	0.090	0.400	522.3

a/ The first letter indicates the type of cement, namely: P=Portland. Z=Portland Pozzolan, L=Lumnite
The second letter indicates the type of aggregate: P=Pumice, H=Haydite, R=Rocklite
The numerals indicate: 1=cured for 28 days only; 2,3,4 and 5 =cured for 28 days and heat treated at 250°C, 500°C, 750°C, 1000°C, respectively.

b/ Specimens were heated at an approximate rate of 50°C per hour to maximum temperature. After equilibrium was reached they were held at this temperature for 5 hours.

c/ See foot notes a and b for details of heat treatment.

d/ The modulus of elasticity and the linear shrinkage were determined on each cylinder of each mix after the 28-day curing. These determinations were made to compare concrete mixes of the same design (See column "Laboratory identification") but made on different days. The results, when compared with those obtained after the several heat treatments, will show any changes in structure of the cylinder that these properties may indicate.

e/ Inaccurate due to strength of cap.

f/ Cement : coarse : thru 9/16 : thru 5/16 : fine.

3. Concretes.

Resistance to abrasion

Test slabs of twelve concretes designed, using each of the three cements, with each of the four aggregates, respectively, were tested for abrasion and the results are given in table 5. The amount of concrete, by weight, abraided from the specimen is considered a measure of its wear in actual service. The loss due to abrasion of the tested specimens ranged from 30 to 2300 grams. In general, the concretes, designed using Lumnite cement, when tested at the age of 28-days, had the least resistance to this type of abrasion. The resistance to abrasion of all concretes irrespective of the aggregates or cements used decreased as the temperature of the heat treatments was increased above 250°C and ranging up to 1000°C.

Figure 2 shows the difference in abrasion resistance of two concretes. Specimen A contained the high-alumina cement and the Haydite aggregate, and had been heated at 750°C. The loss of 2266 grams indicated a comparatively low resistance to abrasion. Specimen B contained the portland pozzolan cement and Waylite aggregate and had been heated at 250°C. It lost 174 grams indicating this concrete had a high resistance to abrasion.

Thermal Conductivity

Figure 3 shows the thermal conductivity of seven lightweight heat-resistant concretes measured at a mean

FIG. 2

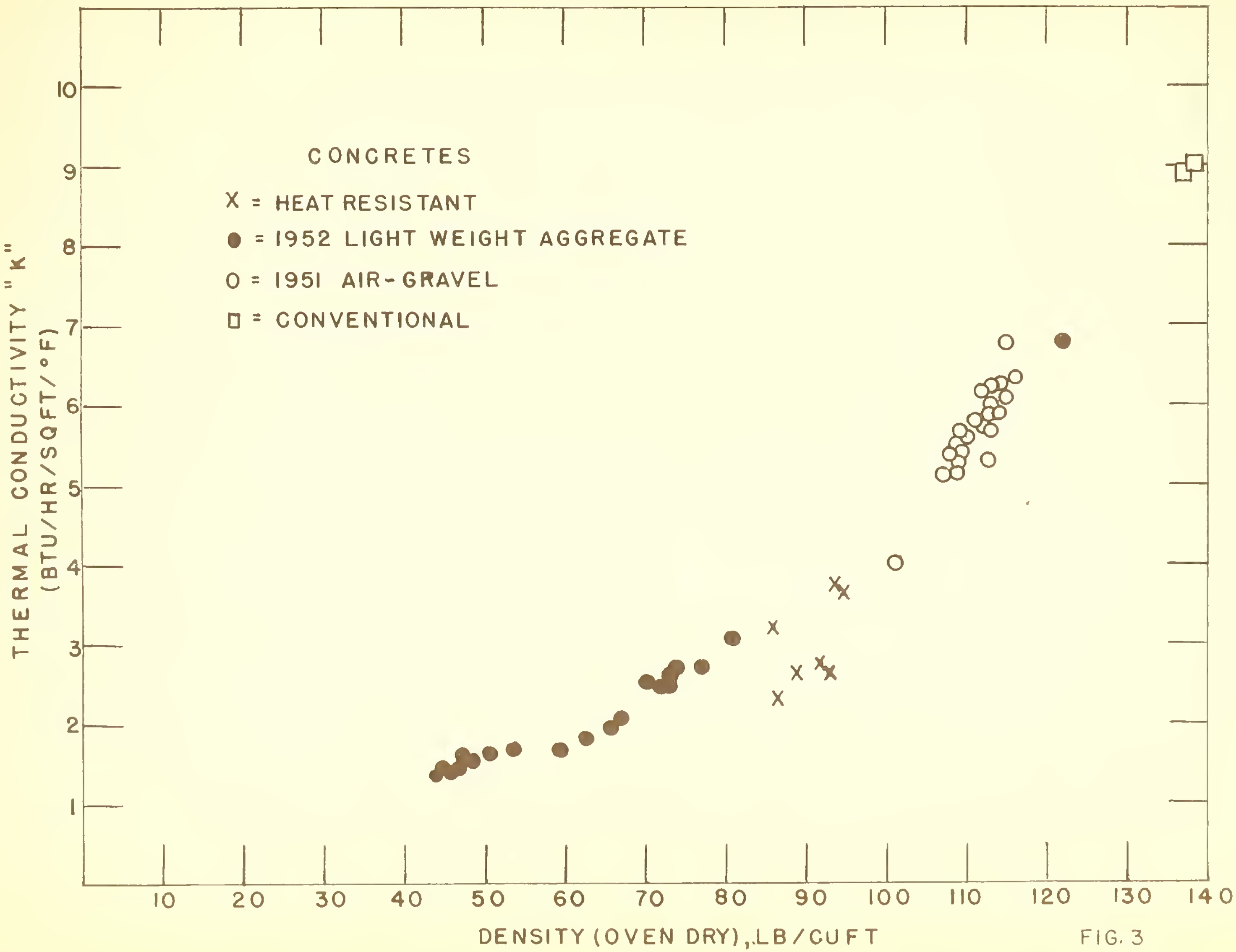
CONCRETES
X = HEAT RESISTANT
● = 1952 LIGHT WEIGHT AGGREGATE
O = 1951 AIR-GRAVEL
□ = CONVENTIONAL
THERMAL CONDUCTIVITY "K"
(BTU/HR/SQFT/°F)
10
9
8
7
6
5
4
3
2
1
10
20
30
40
50
60
70
80
90
100
110
120
130
140
DENSITY (OVEN DRY), LB/CU FT

FIG. 3

temperature of approximately 115°F. The figure not only shows the "k" values for the light-weight heat-resistant concretes included in this investigation but also the "k" values for no fines concretes reported by Valore and Green,[8] as well as unpublished values obtained in an active investigation "High Air-Content Light-Weight Aggregate Concrete."* In addition two "k" values are shown for conventional concrete. The corresponding weight or density (oven dry) in pounds per cubic foot are plotted against these ("k") values. All these results are shown in order that the location of the heat-resistant concretes may be seen with respect to the other types of concretes. The heat-resistant concretes range in density from 85 to 95 pounds per cubic foot and "k" from 2.6 to 3.8. The "k" values in the resulting plotted curve for all concretes have an overall range from 1 to 9 and densities from 40 to 140 pounds per cubic foot so that the heat-resistant concretes fall approximately in the central portion.

Table 5 gives information relevant to the mixed concretes and some of their properties. A good portion of this data is given as a matter of interest to illustrate the wide ranges that exist in such data.

The results given indicate that most of the water loss occurred between the 28-day aging period and 250°C heat treatment. The loss of water continued with successive

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* Building Technology Division, Structural Engineering Section, National Bureau of Standards.

heat treatments to 1,000°C but at a considerably reduced rate. The compressive strengths given in table 5 indicate that only one of the 15 concretes tested met the specified technical requirement of 2600 psi. The one concrete that complied with this requirement contained portland pozzolan cement and the Rocklite aggregate with a 1:1.39 cement-aggregate ratio. It is quite possible that the required strength of 2600 psi might be developed if in one or more of the concretes the cement content were increased. Four of the 12 concretes increased slightly in strength between the 28-day curing period and after the 250°C heat treatment. In all four concretes portland or portland pozzolan cement was used. The strength of the concretes decreases rapidly after heating at 500°C, especially when portland or portland pozzolan cement was used. The concretes containing Lumnite have a tendency to decrease in strength at a slower rate after the 500°, 750° or 1,000°C heating than those containing either of the other two cements.

Modulus of Elasticity

The maximum modulus of elasticity of the concretes, as given in table 5, is approximately 2,000,000 pounds per square inch. Young's modulus for concretes containing pumice, when specimens remained intact so that this property could be determined, was in some instances about one-third that of the concretes made with the other four aggregates.

Heat treating the concretes made with pumice aggregate caused cracking and at some temperatures complete disintogration. The fundamental frequency could not be determined on cracked specimens. In all concretes the modulus decreased rapidly with increasing heat treatments, but when Lumnite cement was used this decrease was less pronounced and tended to level off after heating at 500°C and above.

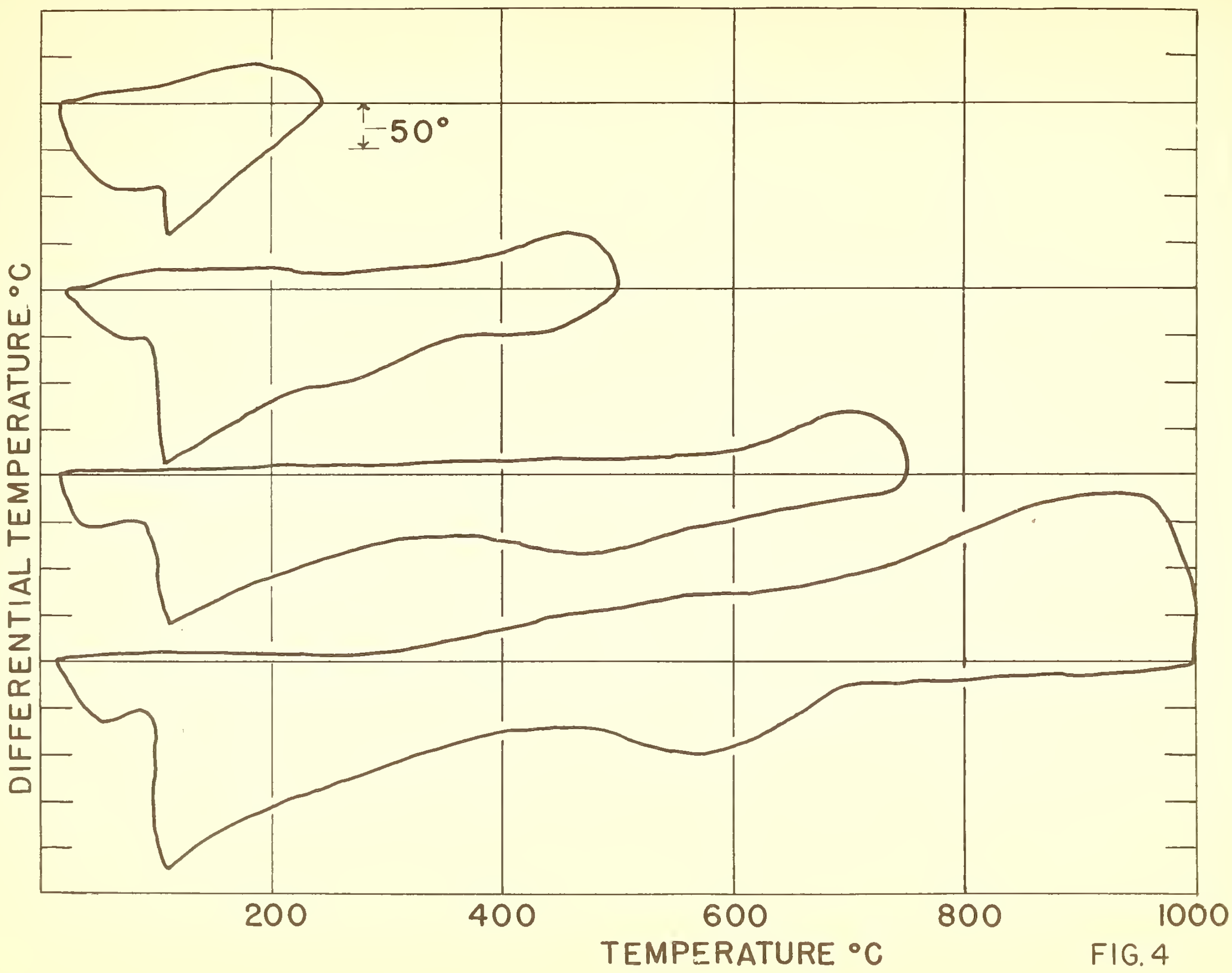
Linear Shrinkage

The linear shrinkage (table 5) after heating at the several temperatures was quite high for the concretes containing pumice aggregate, whereas with the concretes containing any one of the other four aggregates it was considerably less and in some instances a slight expansion occurred after heating at 1,000°C.

Differential Thermal Analysis

Specimens of the concretes were heat treated in a furnace the temperature of which was increased at the rate of 50°C per hour. In order to determine the length of time necessary to reach temperature equilibrium throughout the 12 x 6 inch cylinders a thermocouple was

placed in the center of a cylinder of each concrete and a second attached to the outside and directly opposite the first couple. From the recorded temperatures data was available for determining differential thermal analysis curves. The conventional method of making such determinations is described by Norton. [9] Figures 4, 5 and 6 show thermal curves for four specimens of three concretes designed using the three cements, portland, portland pozzolan, and Lumnite, respectively, with Waylite as the aggregate. All specimens were cured for twenty-eight days before heating. One of each of the four specimens of each concrete was heated at the following temperatures 250, 500, 750 and 1000°C, respectively. The thermal reactions of the three concretes are quite similar. The first inflection, between 50 and 75°C is due to temperature lag. The inverted peak at 100°C is due mostly to the evaporation of free water. The slight inflection occurring between 550 and 650°C indicates the decomposition of calcium hydroxide. This



50°
DIFFERENTIAL TEMPERATURE °C
200
400
600
800
1000
TEMPERATURE °C

FIG. 4

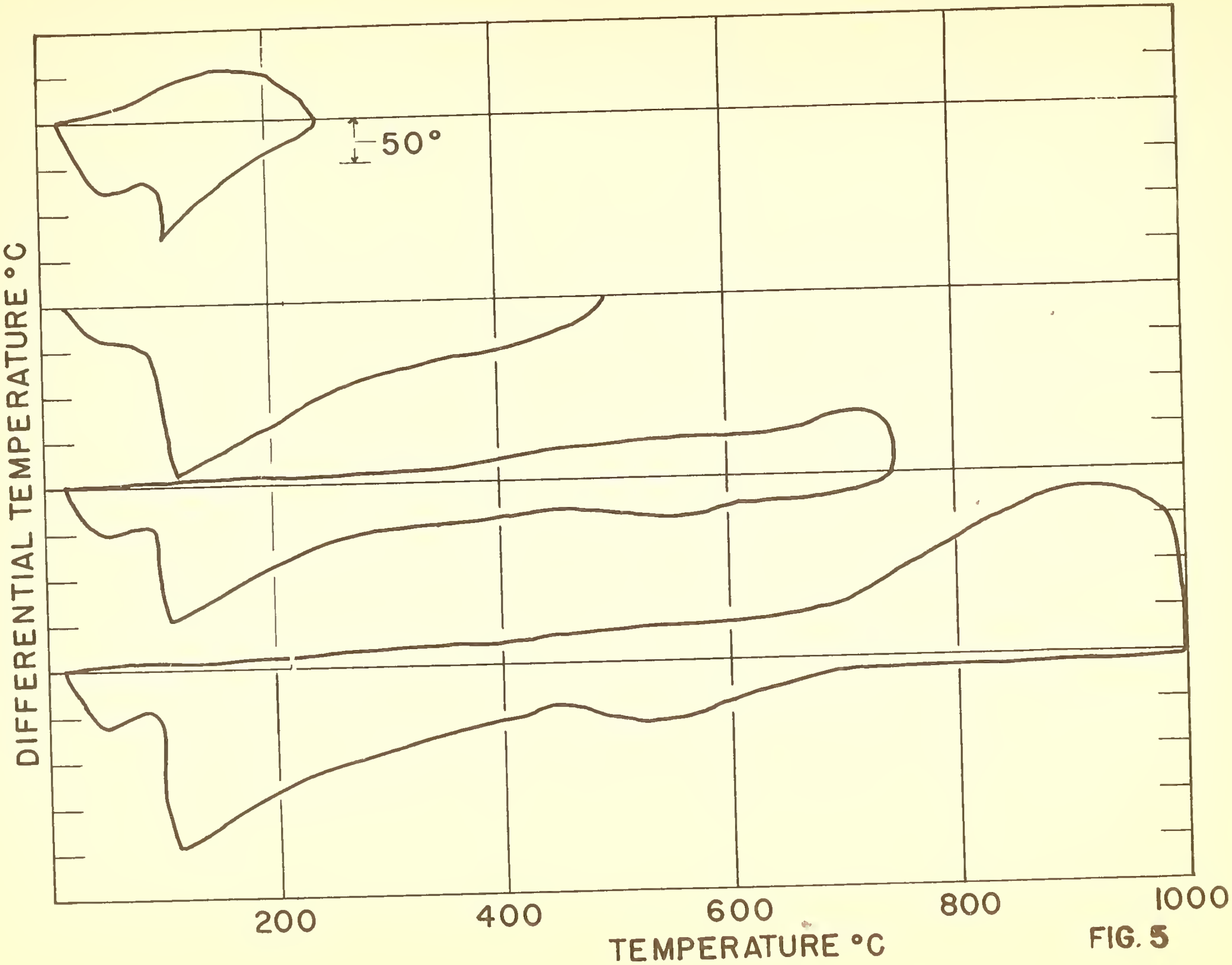
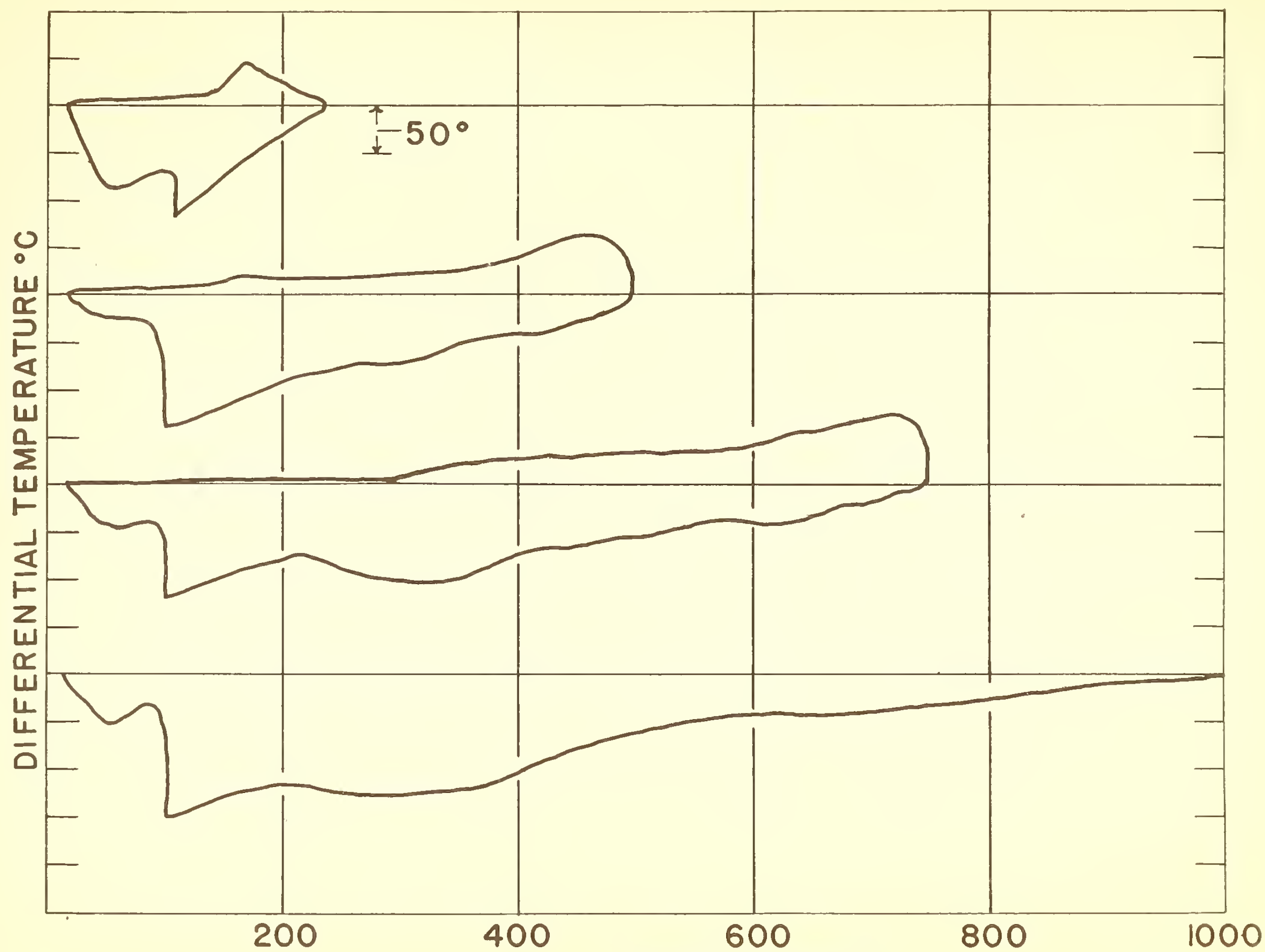

50°
200
400
600
800
1000
TEMPERATURE °C
DIFFERENTIAL TEMPERATURE °C

FIG. 5


50°
DIFFERENTIAL TEMPERATURE °C
200
400
600
800
1000
TEMPERATURE °C
FIG. 6

bulge is more noticeable in figures 4 and 5, the curves for the portland and portland pozzolan concretes. This might be expected since these cements contain nearly twice the amount of calcium oxide present in Lumnite cement. All reactions occur at a slightly lower temperature than was reported by Kalousek, Davis and Schmertz.[10/] A survey of the literature discloses very little published data on the thermal analysis of concretes. For this reason it is included in this report.

V. CONCLUSIONS

As yet insufficient results have been made available to justify any extended conclusions. It may be definitely stated, however, that concretes containing pumice aggregate could not be considered suitable for warm up aprons for jet planes. These concretes not only had low compressive strength after a twenty-eight day curing period but readily disintegrated on heating at elevated temperatures. Although considerable data has already been accumulated the work has not progressed to a point where a definite type of concrete can be

recommended for use in rigid pavements for general ground circulation of jet-type aircraft, for warm up, power check, or take off operations.

1/ Lightweight Aggregate Concrete, issued August 1949.

2/ Standard Method of test for "Pyrometric Cone Equivalent (PCE) of Refractory Materials" ASTM Designation C24-46 Manual of ASTM Standards on Refractory Materials February 1952.

3/ "Properties of Concrete made with Typical Light Weight Aggregates," Materials Laboratory Report No. C-385 June 8, 1948.

4/ "A Portlable Apparatus for Determining the Relative Wear Resistance of Concrete Floors", National Bureau of Standards R.P. 1252, 549.

5/ "ASTM Standards on Mineral Aggregates, Concretes, and Nonbituminous Highway Materials", Sept. 1948.

Compressive Strength of Molded Concrete Cylinders, page 90.

Weight per Cubic Foot, Yield, and Air Content (Gravimetric) of Concrete, page 121.

Slump Test for Consistency of Portland Cement Concrete, page 115.

6/ Proceedings of ASTM Vol. 45, 846 (1945).

7/ Extending Application of the Fineness Modulus. Journal of the American Concrete Institute, Part 2, Dec. 1947 Proceedings V. 43.

8/ "Air Replaces Sand in 'No-Fines' Concrete," Journal of the American Concrete Institute No. 10 (1951).

9/ Critical Study of Differential Thermal Analysis Method for Identification of Clay Minerals. Journal of the American Ceramic Society Vol. 22, 1939, page 693.

10/ An Investigation of Hydrating Cements and Related Hydrous Solids by Differential Thermal Analysis. Journal of the American Concrete Institute, Vol. 20, 1949, page 693.

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